A Computational Study and Analysis of the Blood Flow through Semielliptical Shaped Stenosed Artery

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Abstract

This research study will numerically investigate the impact of semielliptical shape stenosis, and the effect of coronary arterial blockage on blood flow. To explore the differences in flow patterns and hemodynamic parameters under the impact of a single semielliptical shaped artery, a numerical simulation of physiological blood flow via a rigid artery has been be carried out using advanced computational fluid dynamics software called ANSYS WORKBENCH ACADEMIC STUDENT 2024 R1. Fluid flow governing equations solved using finite volume based numerical technique, with the fluid presumed to be viscous, laminar, transient and non-Newtonian. In this study, percentage of stenosis and Reynolds number on flow behavior is investigated. The results will highlight the significant influence of stenosis shape on overall pressure drop and wall shear stress (WSS) across the blocked artery region. To analysis the effect of stenosis severity the size of stenosis is compared with three different stenosis sizes of 35%, 60% and 80%. In actual case, stenosis is irregular in shape, therefore a semielliptical shape stenosis is considered as more relevant to the human cardio vascular system. The findings reveal distinct hemodynamic behaviors associated with each stenosis geometry, offering valuable knowledge for understanding disease progression and potential therapeutic strategies. this research will enhance our understanding of Hemodynamics in stenosis arteries and open the way for more personalized and effective treatment options in managing vascular diseases.

Keywords: Stenosis, Hemodynamic, Computational fluid dynamics, Wall shear stress, Vascular disease

1. Introduction

Stenosis refers to the narrowing of an artery's inner surface, often due to atherosclerosis, a condition characterized by the buildup of lipid deposits in artery walls, forming plaques composed of fat, cholesterol, calcium, and other substances. When a cardiac artery experiences stenosis, it results in decreased pressure and altered flow patterns beyond the blockage. This can lead to various cardiovascular complications, necessitating personalized treatment approaches to manage the condition and prevent further issues. Post-stenosis, blood flow becomes less uniform, with areas of turbulence emerging, influenced by the shape, location, and characteristics of the plaque. Sharp-edged stenoses exacerbate flow disruptions, creating larger separation zones and reduced pressure.

Hemodynamics delves into how blood flow in the cardiovascular system works. Understanding this, it's crucial to recognize that stenosis, an abnormal narrowing of blood vessels due to factors like plaque buildup or inflammation, significantly impacts blood flow in arteries. This narrowing can restrict blood flow to vital organs and tissues, increasing the risk of conditions like renal failure, heart attacks, or strokes. Numerical studies use mathematical models and computational techniques to simulate and analyze complex physical phenomena such as blood flow. By employing numerical analysis, factors like velocity, pressure, temperature, and shear stress in arteries under various conditions can be precisely assessed. This research employs numerical methods to explore blood flow patterns in arteries with semielliptical stenosis. Some previous studies that have investigated similar topics are: Ali et al. [1] employed the finite difference technique to develop a mathematical framework for studying blood circulation within a constricted cylindrical blood vessel. Through the investigation of various parameters, they were able to assess factors such as flow velocity, impedance, wall shear stress, and shear stresses within the stenosis region. Sedeh and Toghraie [2] utilized computational hemodynamics to explore the transfer of heat characteristics of flow of blood across various geometries within the human body, across diverse scales. They examined the influence of dimensionless temperature, Nusselt number, average wall shear stress, and pressure drop, while also taking the heat into account generated during typical bodily functions. Javid et al. [3] introduced a symmetric model incorporating seepage conditions and fluid-structure interactions to analyze the pulsating flow of blood through a compliant stenotic artery. The use of computational fluid dynamics (CFD) is increasingly favored for studying fluid behavior in different applications, providing benefits over conventional experimental fluid dynamics (EFD). CFD can replicate outcomes consistent with in-vivo studies without the limitations, specialized equipment, or high costs associated with traditional experimental methods. Researchers have found CFD to be a dependable method for determining hemodynamic properties, as demonstrated in studies

by Köhler et al. [4], Marshall et al. [5], and Tu et al. [6]. A specific instance within this field involves modeling blood flow through arteries narrowed by semielliptical-shaped blockages, where the shape of the stenosis influences flow characteristics and hemodynamic parameters computational model of an irregular stenotic descending aorta revealed differences in wall shear stress between irregular and regular stenosis models. Irregular stenosis showed stronger wall shear stress (WSS) oscillations at the post-stenotic zone than regular stenosis [7]. Therefore, the main topics covered in previous researches are: The characteristics of blood flow, including velocity, pressure, WSS, and flow separation, are affected by the shape, size, location, and eccentricity of stenosis [8]. The effects of pulsatile flow conditions on stenosis hemodynamics compared to steady flow conditions [9]. The effects of non- Newtonian fluid models on stenosis hemodynamics compared to Newtonian fluid models [10]. The effects of arterial wall compliance on stenosis hemodynamics compared to rigid wall assumption [11]. Despite extensive research on blood flow in stenotic arteries, there has been a need for studies focusing specifically on the influence of different shapes and sizes of stenosis in arteries. This study aims to examine the impact of semi elliptical stenosis shapes on blood flow across varying levels of area.

This study compares various stenosis types and realistic vascular geometry of different degrees of stenosis, with 35%, 60%, and 80% stenosis in the carotid artery being evaluated for simulation. The primary objective is to investigate any variation in Hemodynamics caused by differences in stenosis severity. The plaque, mainly composed of LDL cholesterol and macrophages, worsens atherosclerosis and other vascular diseases. As plaque spreads, it reduces arterial elasticity, causing narrowing and decreased blood flow, known as arterial stenosis. Early detection through imaging and diagnostic methods is crucial for prompt treatment and minimizing negative effects.

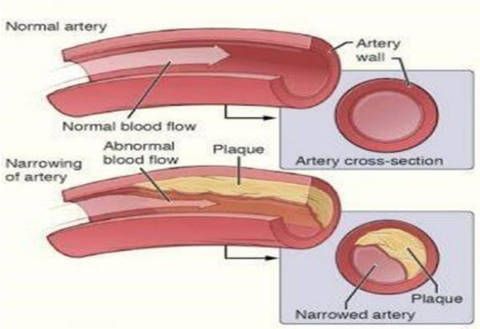


Fig. 1.1. Normal artery vs Atherosclerotic artery [12]

2. Methodology

2.1 Numerical methodology

As shown in Figure 2.1, solving a problem with CFD involves creating geometry, meshing, setting up the physical along with boundary conditions, solving continuity equations, and finally obtaining the results and visualizations. Detailed procedures are discussed in this section.

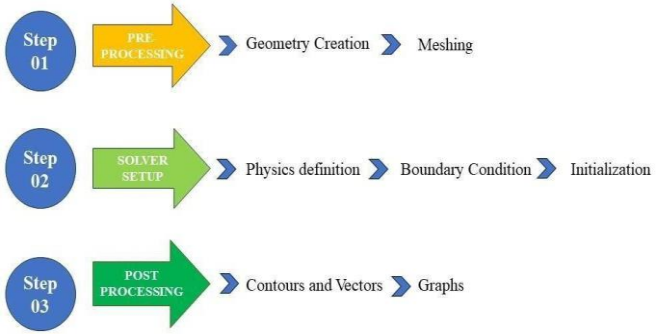


Figure 2.1. Flow Chart Outline of the numerical methodology

2.2 Physical modeling

A human artery can be imagined as a rigid tube. In this case, a two-dimensional rigid tube with a single consecutive blockage is considered for stenosis artery. In an actual case, blood is not a Newtonian fluid. In this study, blood is considered as a non-Newtonian fluid. The flow of blood is considered as steady and laminar. The shape of

stenosis is considered to be semicircular shaped (Figure 2.2) shows the physical geometry of a human artery with a semielliptical-shaped stenosis.

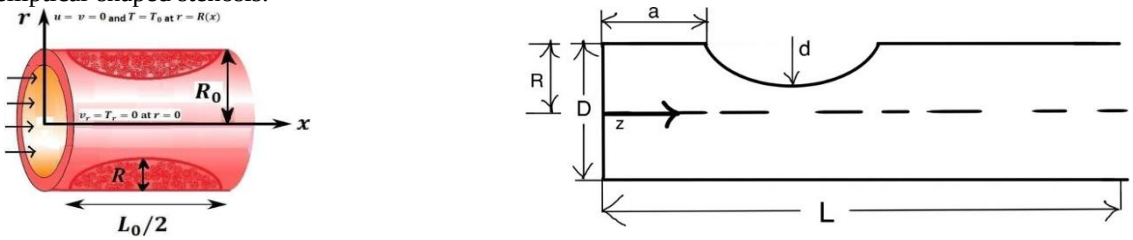


Fig. 2.2. Geometrical structure of arterial stenosis [13] (left) and Geometry of artery with single semielliptical stenosis, where L=125 mm, D=2.5 mm= 2R. Here 'a' is constant (right).

Here, d = radius of semicircular stenosis, d/D = percentage of the stenosis severity R = radius of non-stenotic blood vessel L = length of blood vessel

Case 1: d/D =35% and d= 0.875mm; Case 2: d/D =60% and d= 1.5mm; Case 3: d/D =80% and d= 2mm

2.3 Mathematical Modelling

The continuity equation and the Navier-Stokes equation (NSE) guide the analysis of how fluids move. In two dimensions(2D), the Navier-Stokes equation (NSE) for incompressible flow can be expressed as follows:

$$\partial(\rho V)/\partial t + (V \cdot \nabla) V = -\nabla P + \mu \nabla \hat{}2V + \rho g \quad (2.1)$$

Where: ρ is the fluid density (blood density), t is time,V is the fluid velocity vector (blood flow velocity), ∇ is the del operator (gradient), P is the pressure within the fluid (blood pressure), μ is the dynamic viscosity of the fluid (blood viscosity),∇ ^2V is the Laplacian of the velocity vector, and g is the acceleration due to gravity (usually negligible in blood flow).

Continuity Equation:

$$\partial\rho/\partial t + \nabla \cdot (\rho V) = 0 \quad (2.2)$$

The continuity equation simplifies to:

$$\nabla \cdot V = 0 \ (2.3)$$

Conservation of momentum:

In Cartesian coordinates (x and y directions):

$$\partial(\rho Vx)/\partial t + \partial(\rho VxVx)/\partial x + \partial(\rho VxVy)/\partial y = -\partial P/\partial x + \rho gx + \partial\tau xx/\partial x + \partial\tau xy/\partial y \quad (2.4)$$

$$\partial(\rho Vy)/\partial t + \partial(\rho VyVx)/\partial x + \partial(\rho VyVy)/\partial y = -\partial P/\partial y + \rho gy + \partial\tau yx/\partial x + \partial\tau yy/\partial y \quad (2.5)$$

Where: ρ is the fluid density (blood density in this context), t is time, V is the fluid velocity vector, ∇· (ρV) represents the divergence of the mass flow rate, Vx and Vy are the velocity components in the x and y directions, respectively (blood flow velocity components), x and y are the Cartesian coordinates, ∂/∂x and ∂/∂y are the partial derivatives with respect to x and y, respectively, P is the pressure within the fluid (blood pressure), g is the acceleration due to gravity (usually negligible in blood flow), τxx, τxy, τyx, and τyy are the components of the viscous stress tensor (accounting for the effects of blood viscosity).

2.4 Boundary Conditions

Appropriate boundary conditions were applied to simulate blood flow in stenosis arteries. All the walls in this study will have rigid walls and no-slip boundary conditions. An approximation of the diverse heart rates observed in individuals' velocity profiles was imposed in the inlet. An arterial network model was used to get the velocity profile for the particular artery. All the outlets have zero-pressure outlet boundary conditions.

2.5 Mesh Generation

Mesh is generated by ANSYS WORKBENCH ACADEMIC STUDENT 2024 R1. Three mesh is generated for three different stenosis severity. The physics preference was CFD, fluent was used as solver and the fluent element was linear. The inflation option was first layer thickness. The parameters are shown in table 2.1 below.

Table 2.1: Parameters used for analyzing stenosis severity.

Stenosis severity	Nodes	Elements	Element size (mm)	First layer height (mm)	Maximum layers	Growth rate	Inflation algorithm
35%	10781	19863	0.18	5.95E-02	5	1.2	Pre
60%	10861	20038	0.18	6.82E-02	5	1.2	Pre
80%	10900	20098	0.18	7.00E-02	5	1.2	Pre

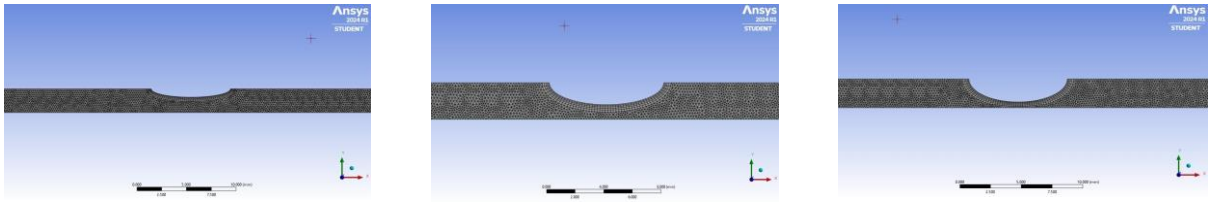


Fig. 2.3. Mesh Generation for 35%, 60% and 80% single semielliptical stenosis respectively

3. Result and Discussion

3.1 Wall shear stress

Wall Shear Stress for 35%, 60% and 80% single semielliptical stenosis respectively are calculated. 7000 iterations each are taken to get the results. Mean Reynold's Number is considered as Re=575. WSS vs. Position(z/D) graph is shown below.

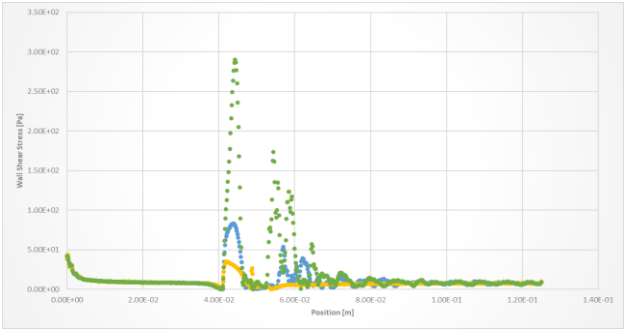


Fig. 3.1. Wall Shear Stress vs. Position graph for 35% (Yellow) , 60% (Blue) , 80% (Green) stenosis with Re=575

When blood flow through a stenotic artery, the velocity increases and pressure decrease. To study the hemodynamic parameters, Wall Shear Stress is a very important parameter. In Figure 3.1, we have seen that Wall Shear Stress is maximum at the position of stenosis throat and minimum at the position of non-stenotic region. Which means wall shear stress is maximum at the point of maximum systolic velocity and minimum at the point of minimum systolic velocity, So, it can be concluded that, wall shear stress increases with the flow velocity.

3.2 Velocity Streamlines

Velocity Streamline for 35%, 60% and 80% single semielliptical stenosis respectively are calculated. 7000 iterations are taken to get the results. Mean Reynold's Number is considered as Re=575. Velocity Streamlines are shown below:

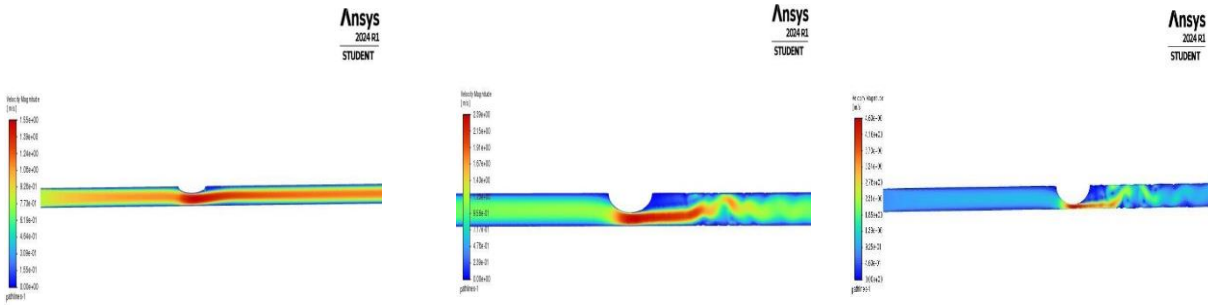


Fig. 3.2. Velocity Streamlines for 80%, 60% and 80% single stenosis respectively with Re=575

3.3 Effect of Reynold's Number on Wall Shear Stress

Reynold's number plays a vital role in the flow field and Wall Shear Stress. That's why to investigate the effects of different Reynold's number on a single semielliptical stenosis we have considered mean Reynold's number Re= 400,575 and 700 with a constant stenosis severity of 80%.

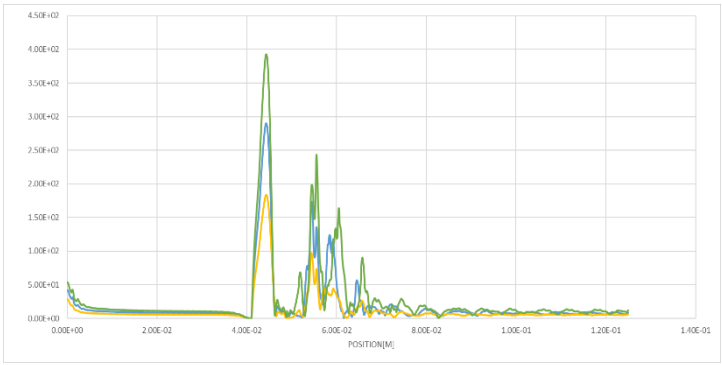


Fig. 3.3. Wall Shear Stress vs. Position Graph for Re=400(Yellow), 575(Blue) and 700(Green) with 80% stenosis severity

It is observed that with the increase of Reynold's number the WSS is considerably increased. For fixed stenosis severity (80%) the maximum WSS occurred at the stenotic throat in each case, but the maximum magnitude of the WSS is higher for higher Reynold's number. Figure 3.3, shows the comparison among WSS for the three Reynold's number considering a constant stenosis severity.

3.4 Validation

In this current investigation, it is imperative to juxtapose the numerical solutions and outcomes to ensure their validity. Verification of the numerical computations should involve cross-referencing with various experimental and analytical solutions pertinent to unsteady laminar flows within a constricted tube. This initial step is crucial for scrutinizing the results. Given that the inlet waveform is sinusoidal, akin to the study by Ojha et al. (1989) [14], it is essential to validate the results against their experiment. However, it's worth noting that their study was experimental, and the fluid properties did not align with the "Carreau-Yasuda" model. Consequently, disparities emerged between the results of the two studies. Nonetheless, the boundary conditions resemble those outlined by Hasan and Das (2008) [15], with the time-averaged wall shear stress showing similarity to their findings.

The current numerical simulation employs the Finite Volume Method (FVM). In this simulation, a basic sinusoidal waveform is applied at the inlet, with subsequent approximation of velocity and Wall Shear Stress using interpolation functions. The computational domain is divided into finite volumes, utilizing tetrahedral elements. The sinusoidal waveform used at the inlet resembles that utilized in a previous study. Figure 3.4 disposes the volumetric flow rate in the simulation of pulsatile blood flow from the aforementioned study [14], while Figure 3.5 illustrates the volumetric flow rate in the simulation of pulsatile blood flow for the current investigation.

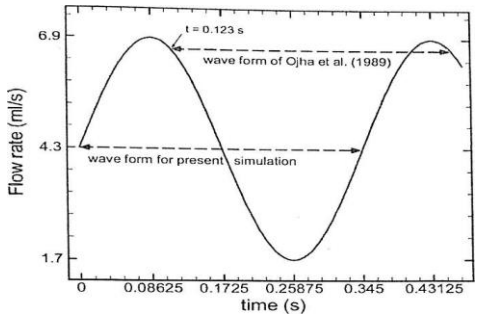


Fig. 3.4. Usual volumetric flow rate in the simulation of blood flow through a human artery [14]

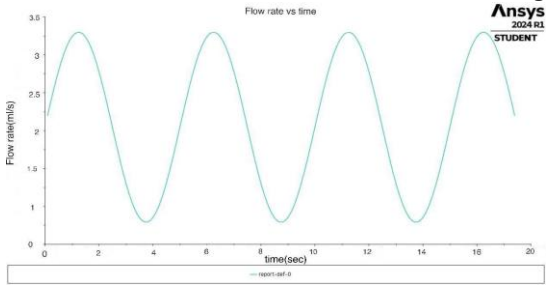


Fig. 3.5. Volumetric flow rate in the simulation of pulsatile blood flow through a human artery for single semicircular stenosis

4. Conclusion

For mechanical and biomedical engineers, understanding hemodynamics and blood flow behavior in arteries with stenosis is essential. Medical applications, such as preventing artery stenosis and assessing patient severity, might benefit from the study of hemodynamic parameters using commercial computational tools like ANSYS WORKBENCH ACADEMIC STUDENT 2024 R1. The ability to assess patient severity before the ailment develops means that this area of research could usher in a new era for humanity. In this present study, investigation of hemodynamic parameters and the computational modeling of physiological blood flow through an artery affected by a semicircular-shaped stenosis is examined. We have seen that the flow field is disturbed after stenosis at maximum systolic velocity. Wall Shear Stress rises to maximum at the position of stenosis. As we have taken a sinusoidal velocity profile at the inlet, the amplitude of the velocity profile at the outlet is greater than the inlet as expected. Effects of stenosis severity is discussed by the means of Wall Shear Stress. This proposal aims to contribute to improved patient care, more accurate diagnostics, and better treatment approaches, advancing medical knowledge in the field of cardiovascular health. The study of hemodynamic parameters under the influence of a stenosis has a number of scopes for the future studies.

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